Setting a New Standard in the Analysis of Binary Stars
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ASTEROSEISMOLOGY OF BINARY STARS AND A COMPILATION OF CORE OVERSHOOT AND ROTATIONAL FREQUENCY VALUES OF OB STARS

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Abstract. After a brief introduction into the asteroseismic modelling of stars, we provide a compilation of the current seismic estimates of the core overshooting parameter and of the rotational frequency of single and binary massive stars. These important stellar parameters have meanwhile become available for eleven OB-type stars, among which three spectroscopic pulsating binaries and one magnetic pulsator. We highlight the potential of ongoing and future analyses of eclipsing binary pulsators as essential laboraties to test stellar structure and evolution models of single and binary stars.

1 The asteroseismic modelling of stars

Asteroseismology is undergoing a revolution since the operation of space missions dedicated (partly) to this subject, such as MOST, CoRoT, and *Kepler* launched in 2003, 2006, and 2009, respectively. The past decade has seen the assembly of uninterrupted white-light space photometry with μmag-precision for thousands of stars that turn out to be pulsating. A thorough introduction into the field of asteroseismology was recently presented in the monograph by Aerts *et al.* (2010) and is thus omitted here. The basic principle of asteroseismic modelling is summarized in one snapshot in the context diagram shown in Figure 1.

Following a too simplistic point of view, one could say that current research in asteroseismology is done with two major aims:

1. To deliver high-precision stellar parameters resulting from the scheme in Figure 1 for exoplanet host stars and for thousands of stars covering large ranges of mass, age, metallicity, and populations in the Milky Way, as input for further stellar and galactic studies. Hereby, it is assumed that the input

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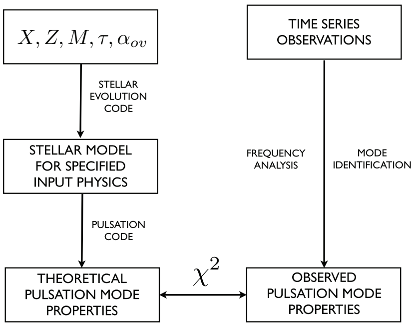

Fig. 1. Schematic representation of the procedure of forward seismic modelling of a massive pulsator with a convective core; τ stands for the age of the star and $\alpha_{\rm ov}$ for its core overshoot parameter expressed in units of the local pressure scale height. Figure courtesy of Dr. Katrijn Clémer.

physics of the stellar structure models is sufficiently appropriate, just as this is assumed in the case when classical data are used to deduce stellar parameters.

2. To improve the theory of stellar structure and evolution, both for single and binary stars, by focusing on the shortcomings of the input physics reflected by too high χ^2-values with respect to the measurement errors.

Even the most basic seismic analysis, based on the frequency of maximum power as well as on the large frequency separation for solar-like pulsators (*e.g.*, Chaplin *et al.* 2011), or on the average period spacing and the periodic deviations thereof for high-order gravity-mode pulsators *e.g.*, Degroote *et al.* 2010), leads to values of the global stellar parameters, such as the mass, radius, and age, with a relative precision of only a few percent, *i.e.*, far better than what can be deduced from photometric colour indices, spectral analysis, interferometric data or present-day astrometry. As a keynote recent illustration of this, the combination of frequency and period spacings of the dipole mixed modes detected in evolved low-mass stars allowed to distinguish between red giants with only hydrogen-shell burning while climbing up the red giant branch or with core helium burning in addition after the helium flash (Bedding *et al.* 2011), a probing that cannot be done from classical data.

So far, the main focus of asteroseismology has been put on item 1. above, *i.e.*, on the derivation of basic stellar parameters, assuming that the input physics of the theoretical stellar models, as indicated in the left part of Figure 1, is correct. This was of course the first thing to do after high-precision data came in. The largest benefit of asteroseismic modelling is, however, yet to come. It requires the detailed modelling of all the individual detected and identified oscillation modes in carefully selected stars of various kinds, in terms of the assumed input physics, with the aim to improve the latter (item 2. above). Intensive future efforts on the left part of Figure 1 are necessary to achieve this, based on joint collaborations between asteroseismologists and experts in the theory of stellar structure. Progress will be made in the next few years by studying the impact of changes in various aspects of the input physics on the oscillation properties, just as it was done in helioseismology to get a better model of the Sun (*e.g.*, Christensen-Dalsgaard 2002 for a thorough review). For the moment, we are not yet at that stage for stars, given the focus on the observational aspects of asteroseismology during the past few years.

2 Compilation of seismic analysis results of OB-type stars

In an attempt to offer new tools to evaluate theoretical stellar models of massive stars in terms of interior mixing processes, Aerts *et al.* (2013) made a compilation of 68 OB-type nearby stars undergoing the CNO cycle in their convective core and studied their observational properties, including oscillations, rotation, magnetic field, and nitrogen abundance, from careful multivariate statistical analysis. This led to the conclusion that the effective temperature and the frequency of the dominant acoustic mode are significant predictors for the nitrogen abundance, while the rotation diagnostics are not. This result implies that the oscillation properties should not be ignored in the evaluation of stellar evolution models.

To trigger further asteroseismic studies of massive stars, including eclipsing binaries, we assembled the eleven stars in the sample by Aerts *et al.* (2013) for which seismic modelling according to the scheme in Figure 1 has been successful and led to a derivation of either a value or an upper limit for the core overshoot parameter $\alpha_{\rm ov}$, based on the Schwarzschild criterion of convection and assuming a fully mixed overshoot region. The spectroscopic and seismic properties of those stars, which are all slow rotators, are listed in Table 1.

Their seismically derived core overshoot parameters are plotted as a function of two observables, $\log T_{\rm eff}$ and $f_{\rm rot}$, in Figure 2, where the three spectroscopic binaries are indicated with full symbols and the one magnetic pulsator has an additional cross indication. By itself, the rotational frequency, which was deduced from Fourier analysis of the seismic data without any model assumption, is not an obvious predictor for the amount of core overshooting. A similar conclusion holds for the mass and the central hydrogen fraction (which is a proxy for the evolutionary state of the star), as can be seen from Figure 3, although the sample is still limited, particularly at high masses. Earlier studies suggested that the core overshoot parameter increases with increasing stellar mass for stars with M$\in$ $[1.1, 1, 7]\,M_\odot$ (Clausen *et al.* 2010, Torres, these proceedings). Asteroseismology shows that this conclusion is too simplistic for stars with masses above $10\,M_\odot$, in line with the results of Claret (2007) based on massive eclipsing binaries.

Staritsin (2013) considered nine of the stars in Table 1 to make three-dimensional hydrodynamical simulations of the extra mixing at the boundary of the convective core, based on the physical model of turbulent entrainment proposed by Meakin & Arnett (2007). He found that the overshoot parameter deduced from

Table 1. Summary of observed ($v \sin i$, $T_{\rm eff}$, $\log g$, $f_{\rm rot}$) and seismically modelled (M, X_c, $\alpha_{\rm ov}$) stellar parameters of 11 OB-type pulsators. The star indicated in bold has a magnetic field while the three spectroscopic binaries are indicated in italic. The data sources of the observed table entries are listed in Aerts *et al.* (2013) and are omitted here for brevity, the references for the seismic modelling results are listed in the last column as a number according to the footnote.

HD number	vsini ($\rm km\,s^{-1}$)	$f_{\rm rot}$ ($\rm d^{-1}$)	$\log T_{\rm eff}$ (K)	$\log g$ (dex)	$\alpha_{\rm ov}$ ($H_{\rm p}$)	Mass ($M_\odot$)	X_c (%)	Ref.
16582	1	0.075	4.327	3.80	0.20 ± 0.05	10.2	0.25	(1)
29248	6	0.017	4.342	3.85	<0.12	9.5	0.26	(2)
44743	23	0.054	4.380	3.50	0.20 ± 0.05	13.6	0.12	(3)
46202	25	—	4.525	4.10	0.10 ± 0.05	24.0	0.58	(4)
129929	2	0.012	4.389	3.95	0.10 ± 0.05	9.4	0.35	(5)
163472	63	0.275	4.352	3.95	<0.15	8.9	0.29	(6)
180642	25	0.075	4.389	3.45	<0.05	11.6	0.23	(7)
214993	36	0.120	4.389	3.65	<0.40	12.2	0.28	(8)
50230	7	0.044	4.255	3.80	0.25 ± 0.05	7.5	0.28	(9)
74560	13	0.010	4.210	4.15	<0.10	—	—	(10)
157056	31	0.107	4.398	4.10	0.44 ± 0.07	8.2	0.38	(11)

(1) Aerts *et al.* (2006), (2) Pamyatnykh *et al.* (2004), (3) Mazumdar *et al.* (2006), (4) Briquet *et al.* (2011), (5) Dupret *et al.* (2004), (6) Briquet *et al.*, (2012), (7) Aerts *et al.* (2011), (8) Desmet *et al.* (2009), (9) Degroote *et al.* (2010), (10) Walczak *et al.* (2013), (11) Briquet *et al.* (2007).

the simulations decreases as the star moves along its evolutionary track (*cf.* his Fig. 3). Our findings represented in Figure 3 are not in contradiction with this conclusion, as can be deduced from *e.g.*, the three stars with seismic mass between 8.9 and 9.5 $M_\odot$, but the sample is not yet suitable to test this result in detail. Such a test would require several seismic estimates of $\alpha_{\rm ov}$ for a particular value of the stellar mass, as a function of X_c.

Unfortunately, we have only two seismic values of $\alpha_{\rm ov}$ for pulsating B stars in close binaries (Table 1), but several new case studies are on the way, such as two SB2 pulsators discovered from *Kepler* data (Pápics *et al.* 2013). Although the current sample is too small to be statistically meaningful, this is one of the important and promising ways towards improving the implementation of the input physics of massive stars.

3 Eclipsing binaries: Complications and opportunties

Given that both the modelling of eclipsing binaries and the seismic modelling of stars are two independent methods to deduce interior physics constraints, among

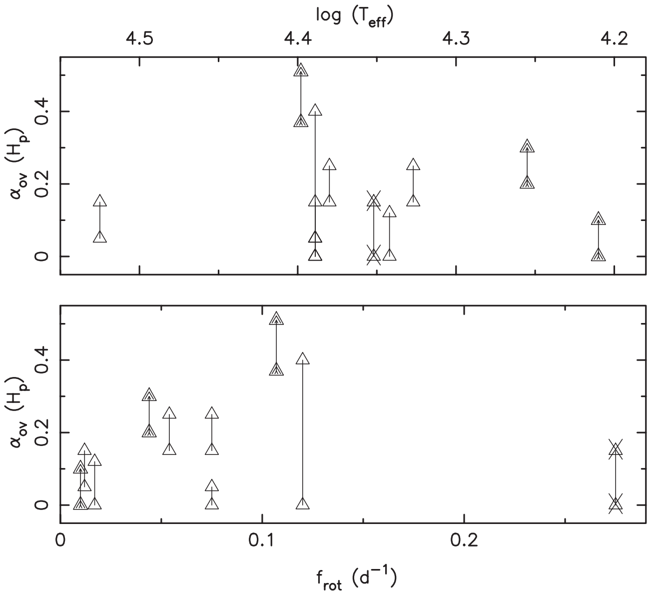

Fig. 2. The core overshoot parameter of OB pulsators as a function of the observed values for the rotational frequency and effective temperature. Open symbols are single pulsators and filled symbols represent spectroscopic binaries with a pulsating component. The cross indicates a magnetic pulsator.

which the overshoot parameter and the age, it is obvious to try and combine them. This idea is not new but good data to bring it into practice with predictive power for the improvement of stellar physics had to await uninterrupted high-precision photometry from space. These data have shown that asteroseismology of pulsating eclipsing binaries turns out to be far from trivial, in part because the binary modelling tools were not up to the precision of the *Kepler* data (*e.g.*, Degroote, these proceedings). Effects like Doppler beaming and gravitational lensing occur at measurable amplitudes reaching several 100 μmag and thus have to be taken into account in the binary modelling to achieve valid interpretations (*e.g.*, van Kerkwijk *et al.* 2010; Bloemen *et al.* 2011, 2012). Conversely, the high quality of the photometric data allows to discover and interpret binarity from careful pulsational analyses thanks to the detection of the Rømer delay, even without having spectroscopic data at hand (Shibahashi & Kurtz 2012; Telting *et al.* 2012).

Both the CoRoT and *Kepler* missions led to the discovery of numerous eclipsing binary pulsators, with a variety of flavours in terms of masses and evolutionary stages of the components (Prša, these proceedings). An extensive overview of pulsating binaries with high-precision photometry by *Kepler* will become available in Huber (2014) while several case studies are discussed elsewhere in the current proceedings. Here, we limit ourselves to highlight a few remarkable case studies of

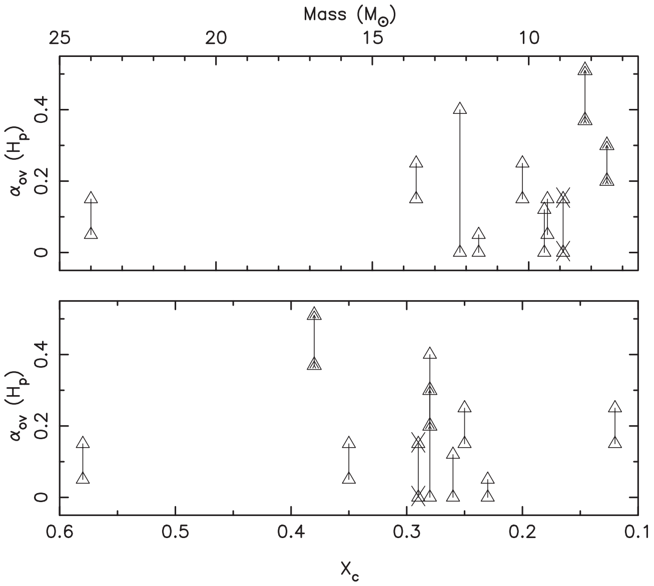

Fig. 3. The core overshoot parameter of OB pulsators as a function of the central hydrogen fraction and the mass as determined from seismic modelling. The symbols have the same meaning as in Figure 2.

pulsating eclipsing binaries, without any effort of being exhaustive and referring to the original papers for details.

The unravelling of pulsational and binary variability, which is a prerequisite for seismic modelling, necessitates rather complex iterative data-analysis schemes when the intrinsic and extrinsic variations have about equal amplitude, such as in the case of the double-lined eclipsing binary KIC 11285625 analysed by Debosscher *et al.* (2013). Even if the data analysis can be successfully accomplished, challenges are faced with the physical interpretation, particularly in the cases where tidally excited g-mode oscillations occur amidst (unidentified) free oscillations of (one of) the components in eccentric systems or when reflection effects are so strong that asymmetrically heated atmosphere models must be used before seismic interpretations can be attempted. Examples of eclipsing binaries with a main-sequence pulsator are, *e.g.*, HD 174884 (Maceroni *et al.* 2009), CoRoT 102918586 (Maceroni *et al.* 2013), KIC 10661783 (Southworth *et al.* 2012; Lehmann *et al.* 2013), and KIC 4544587 (Hambleton *et al.* 2013). The compact subdwarf pulsator 2M1938+4603 requires a new generation of atmosphere models before a solid interpretation can be made (Østensen *et al.* 2010). These case studies represent a variety of situations where the pulsational information was too limited, or was compatible with current-day evolutionary models of single stars, or requires new theoretical developments in atmosphere and interior physics. The latter was the case for the extremely eccentric F-type binary KOI-42 (Welsh *et al.* 2011), where strong forces due to dynamical tides trigger nonlinear resonant locking of pulsation modes (Fuller & Lai 2012).

Easier cases to analyse and interpret were also found, *e.g.*, KIC 8410637 which is a 408-day period eclipsing binary containing a red giant with solar-like oscillations discovered shortly after the launch of *Kepler* (Hekker *et al.* 2010). This object is ideally suited as a test laboratory to evaluate the scaling relations of solar-like oscillations (*e.g.*, Huber *et al.* 2011) as well as to assess isochrone fitting in eclipsing binaries and in open clusters (Frandsen *et al.* 2013). Many other much more complicated red giant binaries with shorter eccentric orbits have recently been found and are being analysed on the basis of *Kepler* photometry combined with long-term follow-up spectroscopy (Gaulme *et al.* 2013; Beck *et al.* 2013).

4 Future studies of massive binary pulsators

While various studies of pulsating eclipsing binaries based on *Kepler* and spectroscopic data are ongoing (*e.g.*, Schmid *et al.*, these proceedings), we are not aware of any such new case studies with OB-type primaries. Unfortunately, pulsating OB-type stars in eclipsing binaries are scarce and the few known ones have insufficient seismic data to tune stellar physics. This is why a *Kepler* guest observer proposal focused on the massive binary V380 Cyg, the brightest star observed by the *Kepler* satellite by means of a dedicated mask. Tkachenko *et al.* (2012) discovered low-amplitude photometric and spectroscopic variability in a preliminary analysis of *Kepler* photometry and high-resolution spectroscopy. Further data gathering and analysis delivered radii and masses of a relative precision near 1%, but pointed out that the line-profile variations are connected with spots of Si while the photometric variability is of stochastic nature with unknown cause (Tkachenko *et al.* 2013). Even without a good explanation of the intrinsic variability of the primary, it was re-emphasized that single-star models cannot explain the components of the V380 Cyg system, not even if we include a high value for the core overshooting.

Interesting ongoing case studies of double-lined spectroscopic binaries with at least one pulsating OB component concern Spica (see also Königsberger, these proceedings) and σ Scorpii, the latter binary's primary being a large-amplitude radial-mode pulsator for which we recently discovered additional low-amplitude modes in an extensive data set of high-resolution spectroscopy (Tkachenko *et al.*, in preparation). So given that the majority of massive stars are in binaries (de Koter, Sana, these proceedings), we are in need of new dedicated observing campaigns to improve their modelling via asteroseismology.

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